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WHITEWATER CLARIFICATION USING A DUAL FLOCCULATION/ ULTRASONIC METHOD

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In mills optimizing raw material usage and closing up water systems due to environmental regulations, efficient techniques are needed to remove accumulating solid suspensions. As a novel approach to solids removal, a dual chemical flocculation/ultrasonic method to clarify a whitewater stream was investigated. The method first considers the use of flocculants to create larger size particles or flocs. Then, an ultrasonic field normal to the flow direction of the whitewater stream is applied to the flocs in such a way as to obtain two output streams: a clarified water stream and a stream of concentrated flocs. A laboratory in-line ultrasonic separation system was used to demonstrate the clarification concept. Different flocculants were tested and experiments at different flow rates, ultrasonic frequencies, and acoustic intensity levels were made. Best results were obtained using the neutral flocculant system PEO/PFR. Test conditions were determined to achieve a clean stream with less than 100 ppm of solids. Also, clarification efficiency close to 80% of the maximum possible clarification efficiency in the experimental setup was obtained. An economic analysis was performed on a theoretical 22,750 L-per-minute (6000 gpm) ultrasonic whitewater clarifier. It was compared to a conventional dissolved air flotation (DAF) unit of the same size. The ultrasonic clarifier is estimated to cost 66% less than the DAF to purchase and install, and will cost 35% less to operate.

and Peterson et al. [10] have been issued patents on ultrasonic separation methods in fluids. In 1990, Apfel [11] reported on the principles and applications of acoustic separation methods. Whitworth et al. [12] reported on the transport and harvesting of fluid-suspended particles using modulated ultrasound. Mandralis and Feke [13] studied the fractionation of suspensions using synchronized ultrasonic and flow fields in 1993. Frank et al. [14] used an ultrasonic field to remove micrometer size particles from water; an enriched suspension and a cleaned fluid were obtained. They indicated that 80% of the particles (40- μm polystyrene latex) could be removed from water. Trampler et al. [15] used ultrasonic resonance fields to induce aggregation and increase the solid sedimentation rate of cells. Klunder and Koopmans [16] studied ash removal in mining pulp using ultrasound in the presence of chemical flocculants. They found that the ash content could be significantly reduced.

The Institute of Paper Science and Technology has been engaged for some time in the development of a novel separation technology relying on ultrasonic principles [17-21]. The technology is aimed at processing large quantities of liquids and/or pulp stocks. More precisely, a traveling (unidirectional) ultrasonic wave field is used to redistribute water suspended particles in such a way as to separate them according to particle radius and to a lesser extent particle density. As a possible industrial application, it was hypothesized that the separation technology could be used to clarify whitewater in a paper mill. Since whitewater solids are relatively small ($<100\ \mu\text{m}$), chemical flocculation was proposed as a simple means to increase particle size in preparation for subsequent ultrasonic clarification. The desired goal is to process a whitewater stream in a continuous mode and obtain two

output streams: a clarified or clean stream and a stream of concentrated solids or flocs. In some ways, the proposed dual flocculation/ultrasonic clarification method can be described as an active sedimentation method into which a weak gravitational force acting on small particles is replaced by a strong acoustic force acting on large flocculated particles.

Dissolved air flotation (DAF) systems are commonly used to clarify whitewater [22]. These passive systems use high pressure to introduce dissolved air in whitewater. When the pressure is released, air microbubbles form and attach themselves to fibers and particles, which then float to the top where they are mechanically skimmed off. The clarification efficiency is greater than 98%. There is an economical incentive to explore alternatives to the DAF technology to drive down the cost of whitewater processing and minimize the use of chemicals. Also, the installation capital cost for a DAF system is significant and a typical DAF system takes up quite a bit of space.

We report a feasibility study of the dual flocculation/ultrasonic whitewater clarification method. The experimental methodology is next described. Then, experimental results are presented and discussed. Finally, an economical assessment of the technology is provided.

EXPERIMENTAL

The experimental methodology was two-fold. First, an optimization study of flocculants suitable for clarification experiments was undertaken. Then, a series of

clarification experiments was performed using an experimental in-line ultrasonic separation system developed at the Institute of Paper Science and Technology.

Flocculant Optimization Study

Whitewater is the filtrate from the forming fabrics of paper machines. Since the chemistry of whitewater is not well documented and varies from mill to mill, three whitewater samples and different flocculants were considered in the study. Table I briefly describes whitewater samples. As seen in Table II, flocculants included an anionic polyacrylamide (APAM), two cationic polyacrylamides with different charge densities (CPAM1 and CPAM2), and a dual flocculant of poly(ethylene oxide) (PEO) with a water-soluble phenolic formaldehyde resin (PFR). These flocculants are widely used as flocculation and retention aids in the paper industry [23]. Charge density was determined by colloidal titration.

Particle size distribution was analyzed using a Malvern System 2600 Laser Particle Sizer. This apparatus was also used to evaluate flocculation efficiency. Since the solids in whitewater are mostly fines and fillers with particle size less than 75 μm , the flocculation efficiency could be evaluated from the amount of particles less than 75 μm in the whitewater before and after flocculation. The number 75 μm was chosen based on the fact that fines can go through a 200 mesh screen which has holes of 75 μm . A typical flocculation test was as follows: a specific amount of flocculant solution was added to 600 ml of whitewater with mechanical stirring at 500 rpm for 10 seconds. The solution was then added to the particle analyzer sample cell, gently stirred, and recirculated at a velocity

of 0.6 m/s; finally, the particle size distribution was analyzed as a function of circulation time.

Figure 1 shows the amount of particles larger than 75 μm for different flocculants using whitewater W3. One observes that the anionic polymer APAM is not effective for whitewater flocculation, while cationic polymers CPAM1 and CPAM2, and neutral dual flocculants PEO/PFR are all very effective. It is known that solid suspensions in whitewater are mainly anionic charged. The electric repulsion between the solid suspensions and the anionic APAM will reduce the adsorption ability of this flocculant, thus preventing satisfactory flocculation. On the other hand, the adsorption of cationic CPAM1 and CPAM2 is facilitated by electrostatic attraction, thus increasing the flocculation efficiency. However, the high cationic demand of the whitewater makes CPAM1 and CPAM2 inefficient at low dosages ($<10 \text{ mg/L}$). The mechanism of PEO/PFR flocculation is different from that of cationic flocculant. A complexation reaction between PEO and PFR is involved in the flocculation [24]. Because PEO is a nonionic polymer, the anionic nature of the suspensions does not affect the flocculation efficiency of PEO/PFR. This flocculant system also shows the best flocculation efficiency at low dosages (2 mg/L PEO:4 mg/L PFR).

The stability of the flocculates formed by the different flocculants (except APAM) is shown in Fig. 2 for whitewater W3. It is observed that the flocs formed by CPAM1 and PEO/PFR slowly break up as a function of time while the flocs formed by CPAM2 cannot resist the shear force and quickly break up. The flocculation of different whitewaters

using the PEO/PFR system was also studied and results are shown in Fig. 3. No obvious effect of whitewater on the flocculation was observed.

Results from the flocculant optimization study led to the conclusion that the PEO/PFR system should perform well during clarification experiments at relatively low dosages. This flocculant system was utilized in all clarification experiments.

Ultrasonic Clarification

Schematic diagrams of the flow and electrical-acoustic systems for ultrasonic clarification experiments are shown in Figs. 4 and 5, respectively. A close-up schematic of the clarification process is also shown in Fig. 5.

As seen in Fig. 4, the main components of the clarification system are a 500-liter feed tank, a 450 L/min centrifugal pump, a vertically-mounted non-pressurized flow cell identified as the in-line acoustic separator, and two 200-liter collection tanks. A mixer is used to prevent sedimentation in the feed tank and a magnetic flow meter is used to monitor the flow rate. Whitewater from the feed tank enters the flow cell from the bottom and passes through a flow development section into the acoustic section. Clean and concentrated output streams exit from the top and are transferred to the collection tanks for sampling. These tanks can be bypassed if desired.

The separator comprises three distinct sections: a flow development section, an acoustic section, and an atmospheric pressure mechanical separation section. The flow development section has a length of 190 cm; its purpose is to control undesirable turbulence patterns from the entrance inlet. Acrylic walls are used on two sides to allow

visual flow inspection. The acoustic section is 30 cm in length and refers to a series of three flush-mounted, 5-cm (W) x 10-cm (L) custom-made piezoelectric ceramic transducers on one side of the cell and three sound absorbers opposite to the transducers (see Fig. 5). The clarification process takes place in this section. Sound absorbers are used to alleviate undesirable reflections of the ultrasonic field in the acoustic section. Transducers and absorbers are removable and easily replaceable. Both the flow development and the acoustic sections have similar rectangular cross sections. One dimension is fixed to 5 cm (corresponding to the width of transducers and absorbers) and the normal dimension (corresponding to the transducer-absorber separation distance) is adjustable from 5 to 15 cm (in 5-cm steps). The mechanical separation section is composed of an adjustable mechanical divider blade whose purpose is to separate clean and concentrated streams. The blade design allows for air to flow through its tip so that flocs don't become stapled to the blade.

The electrical-acoustical system depicted in Fig. 5 illustrates that each transducer can be controlled independently from the others. Function generators (HP Model 33120A) are set to produce continuous sine waves to match the specified operating frequency of the transducers. Outputs from the function generators are fed into broadband power amplifiers (ENI Models 1140LA and 240L) capable of delivering the necessary output power to drive the transducers. As the electrical output impedance of the power amplifiers is $50\ \Omega$ and the electrical input impedance of the transducers is significantly larger, matching impedance networks are used to optimize transfer of electrical power to the transducers.

Built-in meters supplied with the amplifiers are used to monitor the electrical power applied to the transducers. In order to determine the electrical-to-acoustic power efficiency conversion, acoustic-force-equivalent mass balance measurements were performed using individual transducers mounted in a special water tank [21]. Results showed that for transducers operating at 60 kHz, 150 kHz, and 1.5 MHz, the power conversion efficiency factor exceeded 80, 90, and 70%, respectively.

Feasibility Study

Preliminary clarification experiments were conducted at the 5-cm transducer-absorber separation distance. Deflection of flocculated whitewater was easily observed. However, the relatively small separation distance did not facilitate satisfactory sampling of clean and concentrated streams. For this reason, it was decided to increase the separation distance to 15 cm. Also, the mechanical divider was set constant at the middle (50:50) position. When the separation distance was changed from 5 to 15 cm, whitewater samples W1 and W2 were no longer available, and all subsequent results were obtained using only sample W3 (cloudy whitewater from 100% ONP).

Table III summarizes the experimental design for the demonstration of whitewater clarification. All experiments involved varying the acoustic intensity (acoustic power per unit transducer area) at constant transducer frequency and constant flow velocity. Three transducer frequencies were investigated: 60 kHz, 150 kHz, and 1.5 MHz. The flow velocity was varied between 0.1 and 0.4 m/s in increments of 0.1 m/s. This velocity range corresponds to flow rates of 45 to 180 L/min and Reynolds numbers of approximately

7500 to 30,000 at room temperature (turbulent flow regime conditions). Equipment limitations did not allow testing at acoustic intensities higher than 3 W/cm^2 when using 1.5 MHz transducers. The PEO/PFR flocculant dosage was generally set to 5 mg/L:10 mg/L. Additional runs at 1.5 MHz were performed at 2 mg/L:4 mg/L to investigate using the minimum dosage of flocculants.

A typical run involved approximately 180 liters of fresh whitewater in the feed tank. PFR was first added to the whitewater. Once the flow velocity and acoustic intensity were adjusted according to the experimental design, PEO was added, thus triggering flocculation. It is important to mention that the need to recirculate flocculated whitewater (batch mode operation) necessitated the use of flocculants at a higher dosage than would be required under a constant supply of fresh whitewater to compensate for the rapid (and otherwise desirable) degradation of flocculants.

An analog camera connected to a SVHS video recorder was used to record the deflection of flocculated whitewater in the acoustic section. A fiber optic backlight was used to create uniform lighting conditions. Analysis of the video recordings consisted of determining the initial deflection angle θ as depicted in Fig. 5. Three seconds of video (at 30 frames/sec) were digitized and averaged together frame by frame. After the operator identified the initial deflection line, the computer calculated the angle. Five successive three-second segments were analyzed for each recording. Average and standard deviation were then computed. As a first approximation, the initial deflection angle θ can be related to the flow velocity U and the floc migration velocity v (normal to the flow velocity) using the following equation:

$$\tan \theta = \frac{v}{U} \quad (1)$$

One should note that velocity gradients across the flow cell are neglected here.

Assuming that v is constant at constant acoustic intensity, Eq. 1 can be rearranged as,

$$\frac{1}{\tan \theta} = \left(\frac{1}{v} \right) U \quad (2)$$

where $1/v$ is the slope of the linear relationship between $1/\tan \theta$ and U . Eq. 2 can be used to determine v .

Simultaneous sampling of clean and concentrated streams was achieved using 10-liter buckets. Only 500 mL of whitewater was kept for consistency measurements (TAPPI Test Method T 240 [25]) and the leftover liquid was put back in the feed tank to minimize depletion of whitewater for subsequent runs. The flocculation effect degraded after a certain number of runs (can be seen visually), and additional flocculants were added or the whitewater was simply replaced with fresh whitewater.

Finally, equations describing the clean stream solids removal efficiency and clarification efficiency as a function of the divider blade position and feed and clean stream consistencies were derived (see Appendix):

$$\% \text{ Clean Stream Removal Eff.} = 100\% \left(1 - \frac{C_{\text{clean}}}{C_{\text{feed}}} \right) \quad (3)$$

$$\% \text{ Clarification Eff.} = 100\% \left(\frac{\ell_t}{\ell} \right) \left[\frac{C_{feed} - C_{clean}}{C_{feed} \left(1 - \frac{C_{feed}}{100\%} \right)} \right] \quad (4)$$

where C_{feed} and C_{clean} are the percent consistencies of the input feed stream and output clean stream respectively, and ℓ and ℓ_t are the transducer-absorber separation distance and position of the divider blade from the transducer side, respectively. In order to achieve 100% clarification in Eq. 4, all solids must be completely separated from the water, and the divider blade position must be such that only solids are in the concentrated output stream and only water is in the clean output stream.

RESULTS AND DISCUSSION

Several clarification experiments were conducted using whitewater W3 and the flocculant system PEO/PFR. In general, it was found that experiments performed using the 60-kHz transducers were not satisfactory. This may be attributed to a lower threshold for cavitation at this frequency when compared to observations at 150 kHz and 1.5 MHz [21]. For a given amount of acoustic power coming from the 60-kHz transducer, a larger percentage of power is put into cavitation at this frequency than at higher frequencies, and hence, less power is available to deflect the fibers. Therefore, results obtained at 60 kHz are not reported.

Selected frames from the video recordings of the clarification effect at 150 kHz are shown in Figs. 6 through 8. In these figures, flocculated whitewater (dark area) is deflected toward the right (absorbers); white areas represent clarified water. Comparison of Figs. 6 and 7 shows that a 0.1 m/s flow velocity and a 1 W/cm² acoustic intensity

produce a similar deflection effect as a flow velocity of 0.3 m/s and an acoustic intensity of 6 W/cm². While these observations are qualitative and subject to experimental error, they indicate that a more intense ultrasonic field is generally required to counterbalance a larger flow velocity. In both cases, deflection of flocs occurs very early in the acoustic section (bottom transducer position). Although not clearly visible in Figs. 6 and 7, the deflection effect past the initial stage is somewhat mitigated by the presence of undesirable back flows at the walls (edge effects). Possible causes include non-uniformity of the ultrasonic field, undesirable reflections of the ultrasonic field in the acoustic section, and the rectangular cross section of the flow cell. Neither a detailed analysis of the back flows nor any attempt to eliminate them was made.

Figure 8, which involves the excitation of the top transducer only, is interesting because it indicates that an intensity of 10 W/cm² at 0.1 m/s produces a significantly larger deflection than seen in Fig. 6. However, the intensity level is such that the absorber is not very efficient in preventing reflection of the ultrasonic field transmitted through the whitewater. The end result is an apparent mirror deflection effect located in between transducers and absorbers. Optimization of this effect by substituting the absorber by a reflective surface (or a transducer) might provide an alternative approach to the clarification process by collecting flocs from the center of the acoustic section.

Figure 9 provides an example of a recording at 1.5 MHz. To facilitate comparison with Fig. 6, all test conditions but frequency are identical. A smaller initial deflection angle is denoted. However, since undesirable secondary flows are less prevalent at this frequency (presumably because the ultrasonic field is more uniform), floc deflection occurs

over the full length of the acoustic section. This leads to superior clarification efficiency, but at the possible expense of a less economical use of ultrasonic equipment. The reduction in flocculant dosage from 5 mg/L:10 mg/L to 2 mg/L:4 mg/L in Fig. 10 does not significantly degrade the deflection effect seen in Fig. 9 as long as flocculated whitewater is not recirculated several times in the flow system.

Just as excessive cavitation appears to be detrimental to the deflection effect at low frequency (60 kHz), the reduced level of cavitation at 1.5 MHz appears to be counter-productive as well. Because the ratio of the density of air bubbles to water is much smaller than the ratio of the density of flocs to water, air bubbles are easier to manipulate by the ultrasonic field than flocs are. It is possible that cavitation bubbles forming on the surface of the flocs significantly enhance their deflection. Hence, the proper balance between the amount of acoustic power going into bubble formation and the amount available for deflection may lead to optimal deflection of the flocs. At 1.5 MHz, the balance is tipped away from bubble formation, preventing efficient deflection of the flocs. One can hypothesize that the cavitation level at 150 kHz is such that the number and/or size of air bubbles offers a superior set of conditions for floc deflection. Whether or not 150 kHz is an optimized frequency for whitewater clarification remains to be determined through observations at other frequencies between 60 kHz and 1.5 MHz.

The initial deflection angle (see Fig. 5) for all test conditions at 150 kHz and 1.5 MHz was determined according to the method previously described. In agreement with Eq. 2, results expressed as $1/\tan \theta$ versus U are presented in Figs. 11 and 12. Even though some results appear problematic (see below), an overall inspection supports linear

trends. At constant acoustic intensity, $1/\tan \theta$ linearly increases when the flow velocity increases. Also, at constant flow velocity, $1/\tan \theta$ decreases when the acoustic intensity increases. Overlapping of the 150 kHz measurements at 3, 6, and 10 W/cm² (Fig. 11) suggests that there is a plateau for the acoustic intensity. In other words, too much intensity does not improve floc deflection and can be considered as wasted energy. Results gathered at 1.5 MHz (Fig. 12) also show linear trends. Since measurements above 3 W/cm² are not available, the existence of a plateau at/or above 3 W/cm² cannot be confirmed at 1.5 MHz. Difficulties in getting better quality results can be explained by variations in the flow velocity ($\pm 10\%$), the presence of secondary flows (especially at 150 kHz), degradation of the flocculant during experiments, and variations in flocculation efficiency between experiments.

Linear curve fitting applied to the results shown in Figs. 11 and 12 was used to determine the floc migration velocity as a function of acoustic intensity. Results are reported in Fig. 13. Since a strong linear relationship ($R^2 = 0.997$) is observed at 1.5 MHz, it is likely that there is a linear relationship as well at 150 kHz even though data points are more scattered. Larger velocities at 150 kHz confirm that energy is more efficiently used at this frequency in the initial stage of deflection.

Consistency measurements performed on the clean and concentrated output are shown in Figs. 14 and 15 for experiments at 150 kHz and 1.5 MHz, respectively. Even though there is a distinctive change in consistency between the two output streams at 150 kHz (Fig. 14), secondary flows present at this frequency adversely affected performance. Also, too much intensity (e.g., at 10 W/cm²) further degrades performance as previously

observed in Fig. 8. Consistency results at 1.5 MHz (Fig. 15) show larger changes in consistency between the two output streams (between 80 and 90%). The clean stream consistency is less than 0.01% or 100 ppm of solids, i.e., in agreement with measurements typically obtained using a DAF system.

The clean stream solids removal efficiency and clarification efficiency were determined using Eqs. 3 and 4. Results are presented in Figs. 16 and 17 for 150 kHz and 1.5 MHz observations, respectively. As expected from consistency measurements, best efficiency results were obtained at 1.5 MHz. Since the divider blade position was set to 50:50, the limit of maximum achievable clarification efficiency is 50%. Hence, the nearly 40% clarification efficiency at 1.5 MHz corresponds to 80% of the maximum achievable clarification efficiency. This is not anywhere close to the clarification efficiency obtainable using a commercial DAF system (higher than 90%). However, as illustrated in the Appendix, one expects optimization of the ultrasonic technology to provide a comparable level of efficiency.

ECONOMICAL ASSESSMENT

A preliminary economical assessment of the clarification method was conducted. Chemical costs for PEO and PFR are approximately \$5/kg (\$5k/ton) and \$1/kg (\$1k/ton), respectively. This means that the cost associated with using these chemicals at the 5 mg/L:10 mg/L and 2 mg/L:4 mg/L dosages are \$0.035/1000 L (\$0.133/1000 gal.) and \$0.014/1000 L (\$0.053/1000 gal.), respectively. Since the need to maintain flocculation for several cycles would not apply for continuous in-line treatment in a mill environment,

the use of a lower dosage level is expected, and hence, anticipated chemical costs should be lower than the above figures.

Initial deflection angle measurements presented in Figs. 11 and 12 were used to predict the operating cost of a hypothetical whitewater ultrasonic clarification system aimed at increasing the feed stream consistency by a factor of 10. The basis for comparison is a 22,750 L-per-min (6000 gpm) commercial DAF system. Table IV shows capital (including installation cost in the mill) and operation costs for the DAF system and ultrasonic clarifier. It is assumed that the ultrasonic clarifier operates under the following conditions: frequency of 150 kHz, flow velocity of 0.3 m/s, and acoustic intensity of 3 W/cm². Also, the PEO/PFR flocculant dosage is 2 mg/L:4 mg/L. For this scenario, a unit-annualized cost of \$0.025/1000 L (\$0.094/1000 gal.) is estimated for the ultrasonic clarifier (including chemical costs). Further reductions in capital and operating costs are expected in the future due to improved efficiency and lower part costs, as well as expected lower chemical demand. Installed capital is based upon 1999 part costs and includes installation.

OTHER BENEFITS OF THE ULTRASONIC CLARIFIER

In addition to the installation and operating cost reductions with the ultrasonic technology, there are several other advantages over a conventional DAF. First, the ultrasonic clarifier will be much smaller in footprint. A 22,750 L-per-min clarifier will require less than 5 square meters (55 square feet) of floor space, compared to the several hundred square meters (several thousand square feet) for a DAF of the same size. Second, because the ultrasonic clarifier is a closed system, no special environmental

equipment will need to be installed in conjunction with the clarifier to control emissions because there will be no open surface for emissions to escape. This will become a more important issue as mills proceed to close up their water supplies and contaminants trapped in the water system build up and look for escape routes.

CONCLUSIONS

A laboratory feasibility study using chemical flocculation in combination with an ultrasonic wave field to clarify whitewater was reported. In a preliminary set of experiments, different flocculants were tested and the neutral flocculant system PEO/PFR was determined to be the most effective for clarification experiments. The PEO/PFR system required the lowest dosages and produced the largest and most stable flocs of the flocculants tested. PEO/PFR was also found to be equally effective on all three whitewater samples tested.

A series of cloudy whitewater clarification runs was then undertaken. Experiments were performed at three different frequencies (60 kHz, 150 kHz and 1.5 MHz) for different flow velocities and acoustic intensities. A video camera was used to record the deflection of flocs and the initial deflection angle was measured. It was found that 150 kHz produces larger deflections than 60 kHz or 1.5 MHz. This was thought to be due to optimal energy split between the ultrasonic field and production of cavitation bubbles.

A trend of increasing deflection angle with increasing acoustic intensity was seen at 150 kHz, up to an intensity of 3 W/cm^2 . Beyond this, an increase in intensity did not yield significantly higher deflection angles. Increasing flow velocity at constant acoustic

intensity reduced the deflection angle. This was observed at both 150 kHz and 1.5 MHz. This is due to lower dwell times in the ultrasonic field as the flow velocity increases.

In addition to video deflection angle measurements, the consistency of the clean and concentrated output streams was measured and the clean stream solids removal efficiency and clarification efficiency were computed. Clarification efficiency was largest at 1.5 MHz, reaching nearly 40% (the maximum achievable was 50% due to the 50:50 divider blade position – no attempt was made to optimize the divider blade position). Lower flow velocities (longer dwell time in the ultrasonic field) improved the clarification efficiency at both 1.5 MHz and 150 kHz. Acoustic intensity did not significantly affect the clarification efficiency at 1.5 MHz, but an optimum of 3 W/cm^2 was found for 150 kHz.

An economic analysis was performed on a theoretical 22,750 L-per-minute (6000 gpm) ultrasonic whitewater clarifier. It was compared to a conventional dissolved air flotation (DAF) unit of the same size. The ultrasonic clarifier is estimated to cost 66% less than the DAF to purchase and install, and will cost 35% less to operate (considering both chemical and electrical costs).

Various improvements can be made to further optimize the clarification technology. The geometry of the flow cell can be redesigned to minimize secondary flows to optimize clarification efficiency at 150 kHz. While 150 kHz produced the largest deflection angles, and 1.5 MHz achieved the highest clarification efficiencies, other frequencies need to be evaluated to see if further advances can be made. With respect to clarification efficiency, no attempt was made to optimize the divider blade position.

Instead, experiments were only performed with the divider blade at the 50:50 position, limiting the maximum clarification efficiency to 50%. Because the laboratory separation system works in a closed loop mode, the flocculant concentration needed to be higher than would be necessary in a continuous system to compensate for degrading of the flocs as they made multiple passes through the pump. Also, work is ongoing to better understand the interaction between cavitation bubbles and the ultrasonic field, which may lead to optimization of energy transfer from the transducer to the flocs.

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Appendix A – Clarification Efficiency

In order to achieve 100% clarification efficiency, both the divider blade position and the clean stream solids removal efficiency should be optimized, i.e.,

$$\% \text{Clarification Eff.} = (\text{Optimal Divider Position}) (\% \text{Clean Stream Removal Eff.}) \quad (\text{A1})$$

Referring to Fig. A1, the clean stream consistency is optimized when it goes to zero.

Hence, the clean stream solids removal efficiency is given by,

$$\% \text{Clean Stream Removal Eff.} = 100\% \left(1 - \frac{C_{\text{clean}}}{C_{\text{feed}}} \right) \quad (\text{A2})$$

where C_{clean} is the % clean stream consistency and C_{feed} is the % feed stream consistency.

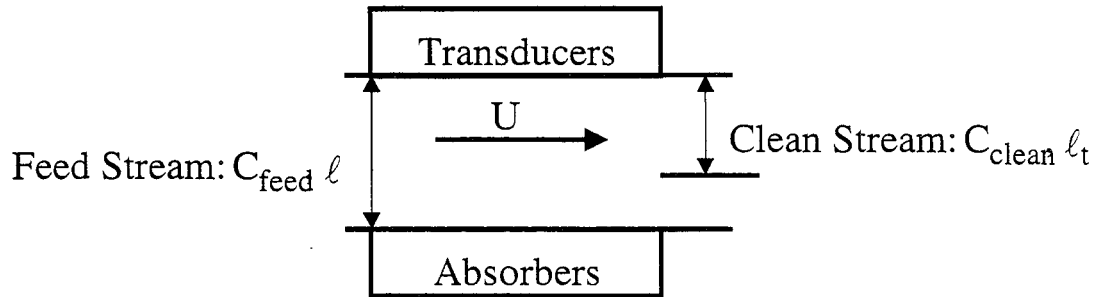


Fig. A1. Geometry of flow cell. C_{feed} and C_{clean} are the % feed and clean stream consistencies, respectively. U is the flow velocity, l is the separation distance between the transducers and absorbers, and l_t is the distance between the transducers and the divider blade.

The divider position is optimized when it reaches the position furthest from the transducer that is theoretically possible. Referring to Fig. A2, if the water and suspended particles (flocs) are 100% separated, with pure water on the top of the cell and only flocs on the bottom, the water forms a layer l_{water} thick, and the flocs forms a layer $l - l_{\text{water}}$ thick.

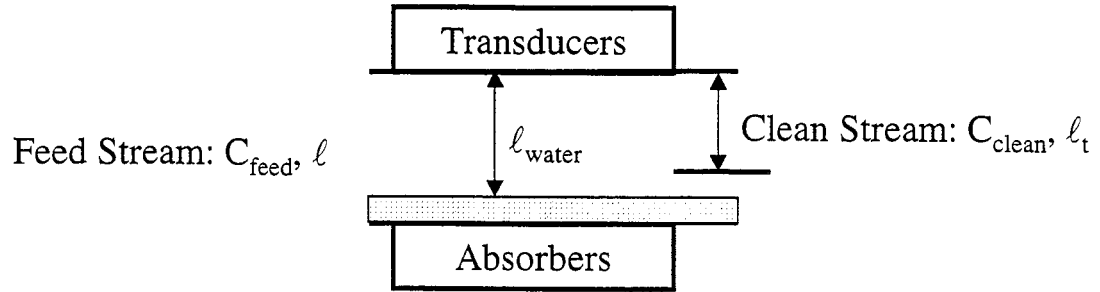


Fig. A2. Flocs on bottom of flow cell are completely separated from water on top of flow cell. Thickness of the water layer in this case = ℓ_{water} .

Hence, optimal divider position is achieved when $\ell_t = \ell_{\text{water}}$, which can be written mathematically as:

$$\text{Optimal Divider Position} = \left(\frac{\ell_t}{\ell_{\text{water}}} \right) \quad (\text{A3})$$

The thickness of the water layer for 100% separation is simply the percent water in the feed stream $[(100\% - C_{\text{feed}})/100\%]$ multiplied by the cell width (ℓ):

$$\ell_{\text{water}} = \ell \left(1 - \frac{C_{\text{feed}}}{100\%} \right) \quad (\text{A4})$$

Hence combining Eqs. A3 and A4 yields

$$\text{Optimal Divider Position} = \frac{\ell_t}{\ell \left(1 - \frac{C_{\text{feed}}}{100\%} \right)} \quad (\text{A5})$$

Substituting Eqs. A2 and A5 into Eq. A1 then gives the clarification efficiency:

$$\% \text{Clarification Eff.} = 100\% \left(\frac{\ell_t}{\ell} \right) \left[\frac{C_{\text{feed}} - C_{\text{clean}}}{C_{\text{feed}} \left(1 - \frac{C_{\text{feed}}}{100\%} \right)} \right] \quad (\text{A6})$$

In order to illustrate Eq. A6 and the hypothetical performance of an acoustic clarifier, one can consider a whitewater stream entering the flow cell at 0.03% consistency. If the clean stream consistency is 0.001%, and the divider blade is placed at 97% of the way across the flow cell ($\ell_v\ell = 0.97$), the efficiency of the clarification process is then

$$\% \text{Clarification Eff.} = 100\% (0.97) \left[\frac{0.03\% - 0.001\%}{0.03\% \left(1 - \frac{0.001\%}{100\%} \right)} \right] = 94\%$$

This is comparable to a typical DAF system.

TABLE I
WHITEWATER SAMPLES USED IN THE STUDY

Whitewater Sample	Description	Particle size distribution (% < 75 μm)	Consistency (%)	Colloid titration (meq/L)
W1	From 24% OCC and 76% unbleached kraft softwood	97%	0.054	-0.42
W2	From 100% OCC	78%	0.072	-0.30
W3	From 100% ONP (Cloudy whitewater)	72%	0.036	-0.28

TABLE II
FLOCCULANTS USED IN THE STUDY

Symbol	Flocculant	Chemical Composition	Charge Density (meq/g)	Supplier
APAM	Percol 172	Anionic PAM	-0.315	Allied Colloids
CPAM1	Percol 175	Cationic PAM	1.0	Allied Colloids
CPAM2	7523	Cationic PAM	0.163	Nalco
PEO	PEO*	Poly(ethylene oxide)	0	Aldrich

*One part of PEO is used with two parts of phenolic formaldehyde resin (PFR, from Borden Chemicals) in flocculation.

TABLE III
EXPERIMENTAL DESIGN

Transducer Frequency	PEO/PFR Dosage	Flow Velocity (m/s)	Acoustic Intensity (W/cm ²)					
			0	1	2	3	6	10
60 kHz	5 mg/L:10 mg/L	0.1	X	X	X	X		
150 kHz	5 mg/L:10 mg/L	0.1	X	X	X	X	X	X
		0.2	X	X	X	X	X	X
		0.3	X	X	X	X	X	X
		0.4	X	X	X	X	X	X
1.5 MHz	5 mg/L:10 mg/L	0.1	X	X	X	X		
		0.2	X	X	X	X		
		0.3	X	X	X	X		
		0.4	X	X	X	X		
1.5 MHz	2 mg/L:4 mg/L	0.1	X	X	X	X		
		0.2	X	X	X	X		

TABLE IV
ESTIMATED COST FOR A 22,750 L-Per-Min (6000 gpm) HYPOTHETICAL
ULTRASONIC CLARIFICATION SYSTEM AND COMMERCIAL DISSOLVED
AIR SYSTEM

Item	Ultrasonic Clarifier (\$k)	DAF System (\$k)
Capital and Installation Cost	352	1073
<i>Annual Energy Cost for Ultrasonic Equipment</i>	45	0
<i>Annual Energy Cost for Pumping</i>	8	103
<i>Annual Chemicals Cost</i>	168	250
Total Annual Operating Cost	221	353

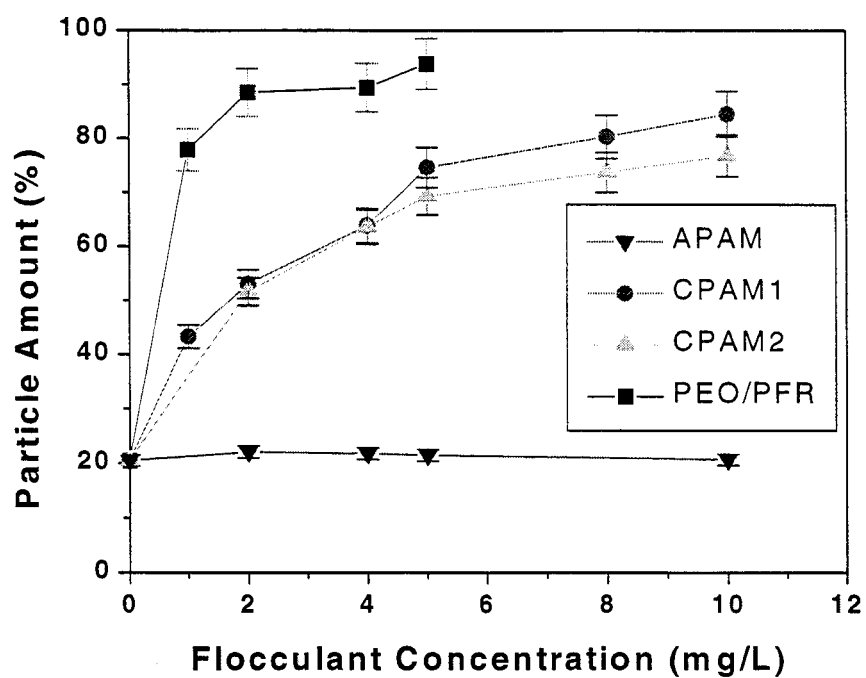


Fig. 1. Amount of particles (%) greater than 75 μm in whitewater W3 as a function of flocculant dosage for the flocculants listed in Table II. The circulation time is one minute in the particle sizer.

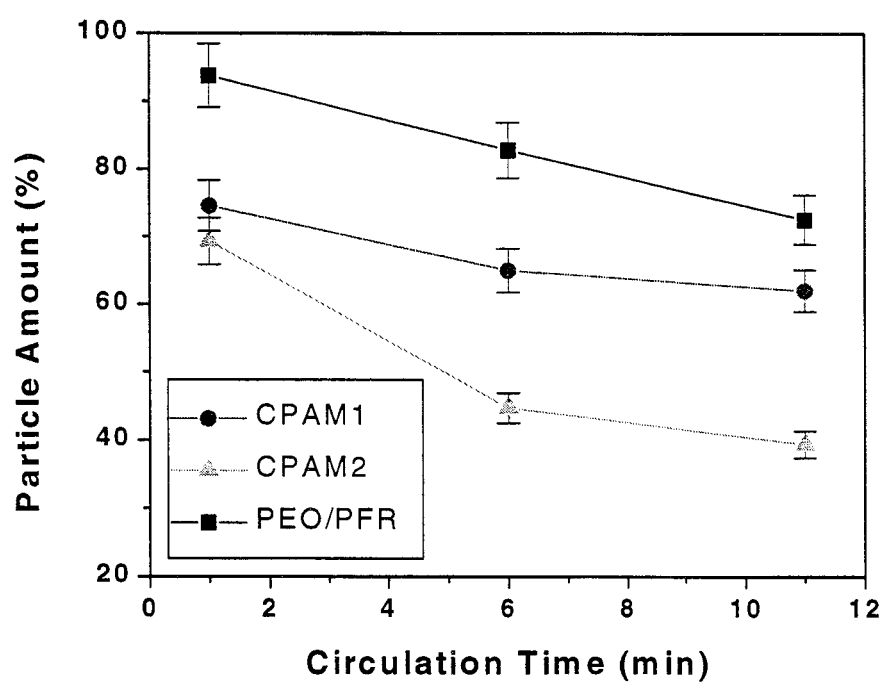


Fig. 2. Amount of particles (%) greater than 75 μm as a function of circulation time for whitewater W3. The flocculant dosage and circulation velocity are 5 mg/L and 0.6 m/s, respectively. Circulation was done in the particle sizer.

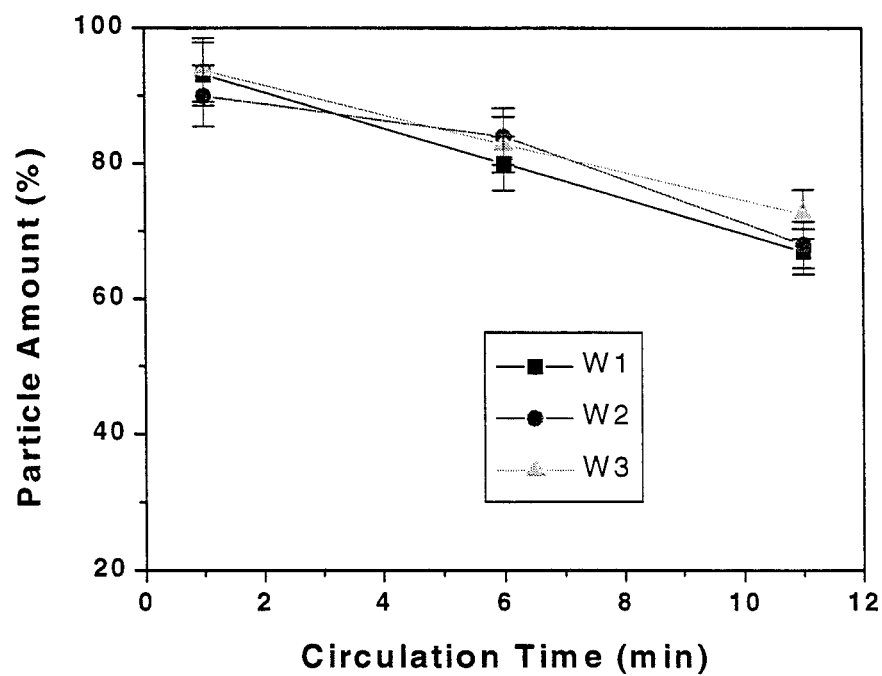


Fig. 3. Amount of particles (%) greater than 75 μm as a function of circulation time in the particle sizer for whitewaters W1, W2 and W3 (see Table I) using the PEO/PFR flocculant system. The dosage is 5 mg/L:10 mg/L.

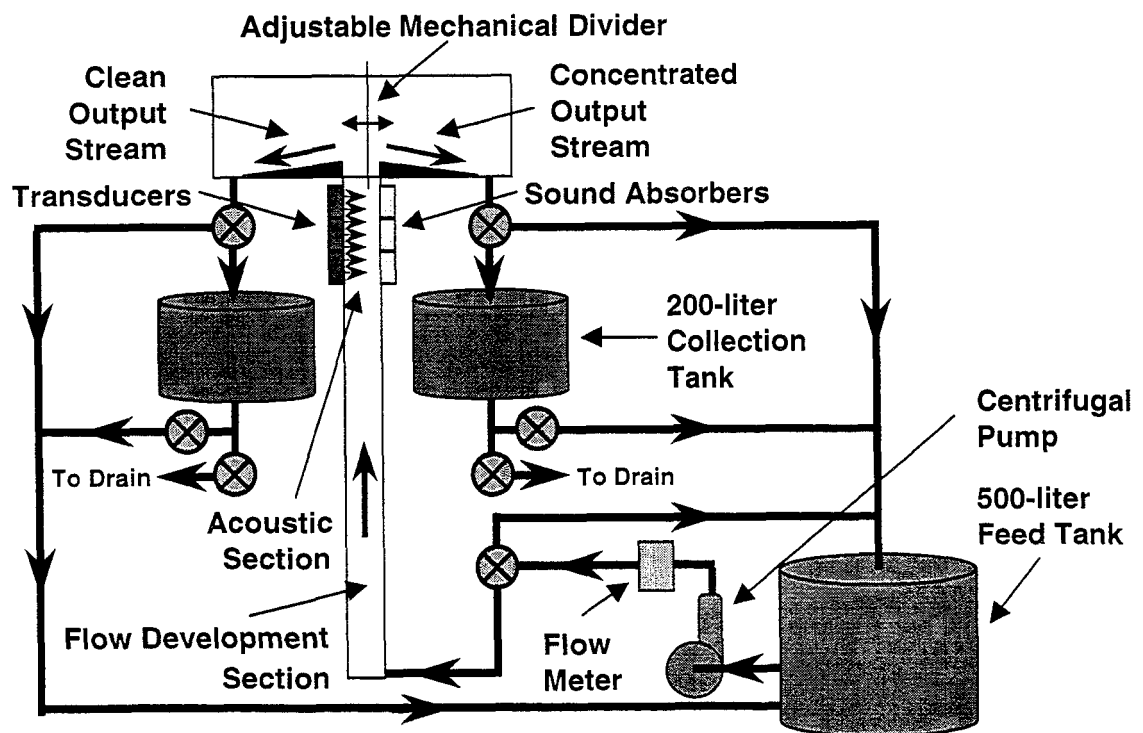


Fig. 4. Schematic diagram of the flow system for clarification experiments. Whitewater flows from bottom to top in the vertically-mounted pipe located between the 200-liter collection tanks. The clarification process takes place in the acoustic section.

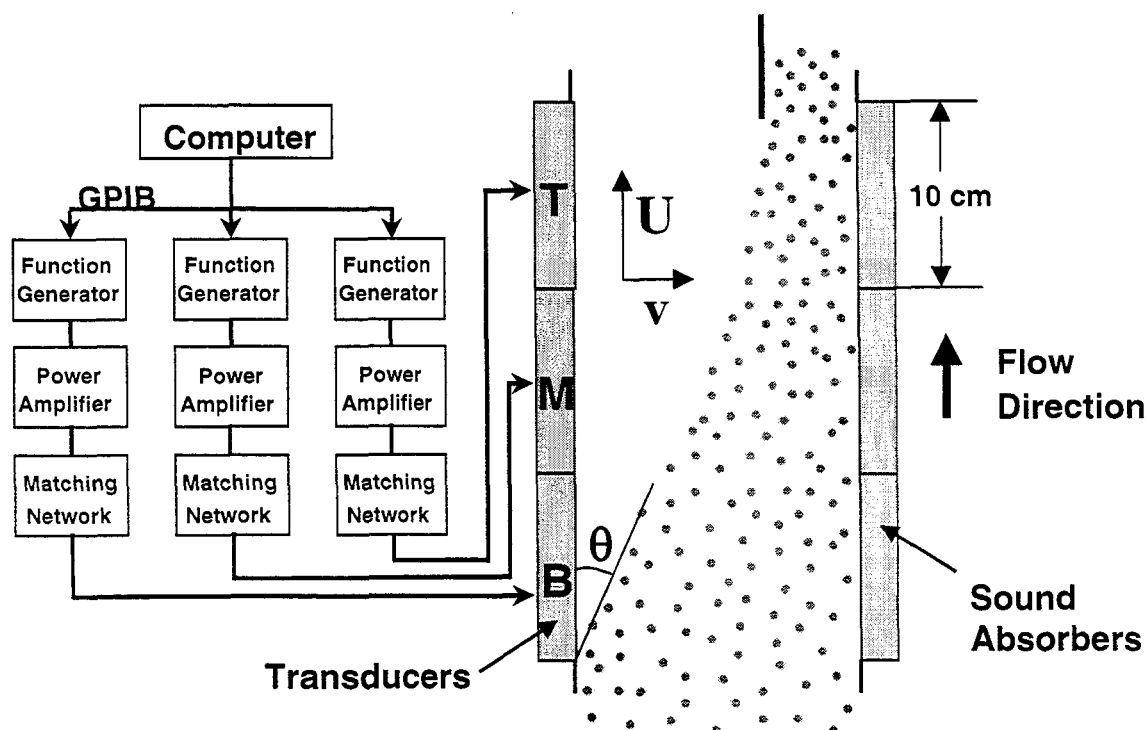


Fig. 5. Schematic diagram of computer-controlled electrical/acoustical system and close-up of clarification process. T, M, and B refer to Top, Middle, and Bottom ultrasonic transducers, respectively. U and v represent the flow and floc migration velocities, respectively. Flocs are deflected toward the absorbers by an angle θ as they move upward and interact with the ultrasonic field.

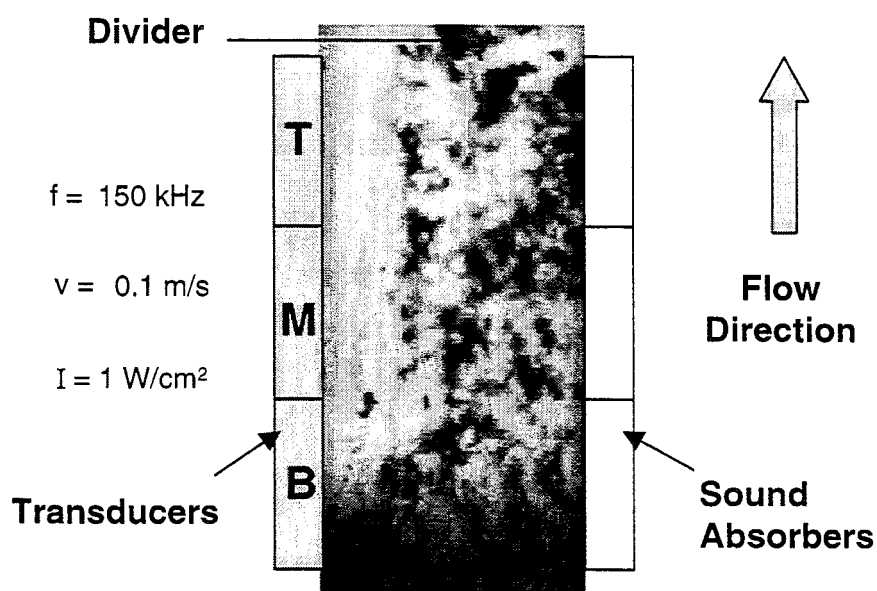


Fig. 6. Whitewater clarification using three 150 kHz transducers. The PEO/PFR level is 5 mg/L:10 mg/L.

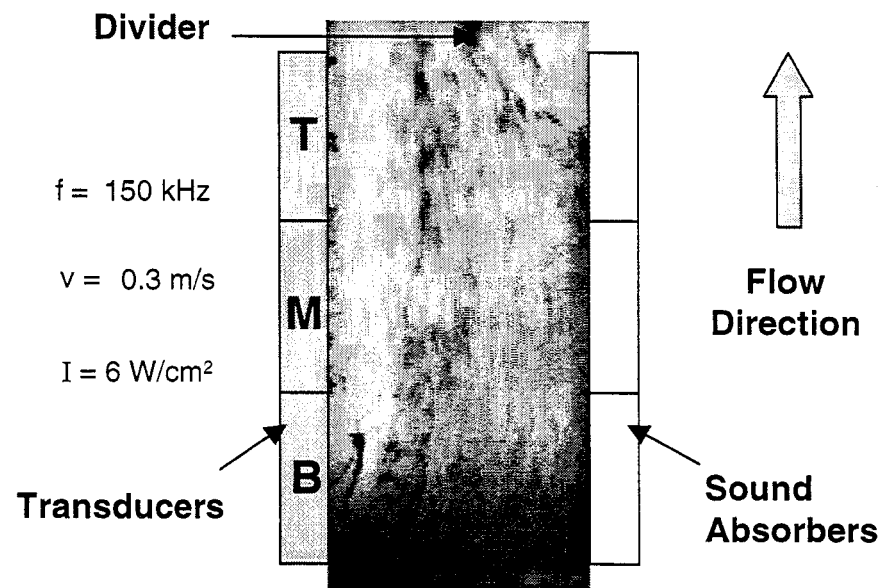


Fig. 7. Whitewater clarification using three transducers operating at 150 kHz. The PEO/PFR level is 5 mg/L:10 mg/L.

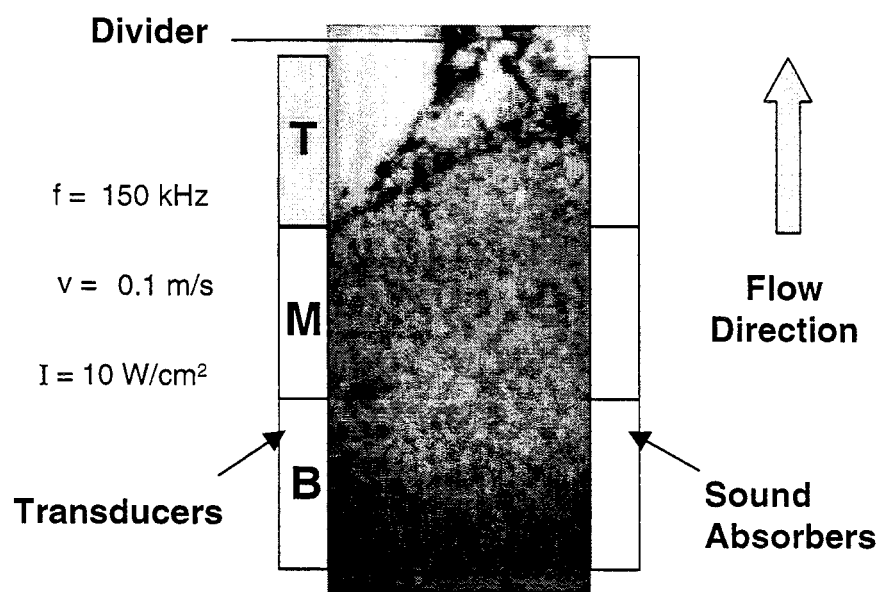


Fig. 8. Observation of clarification using only the top transducer. The transducer frequency is 150 kHz. The PEO/PFR level is 5 mg/L:10 mg/L.

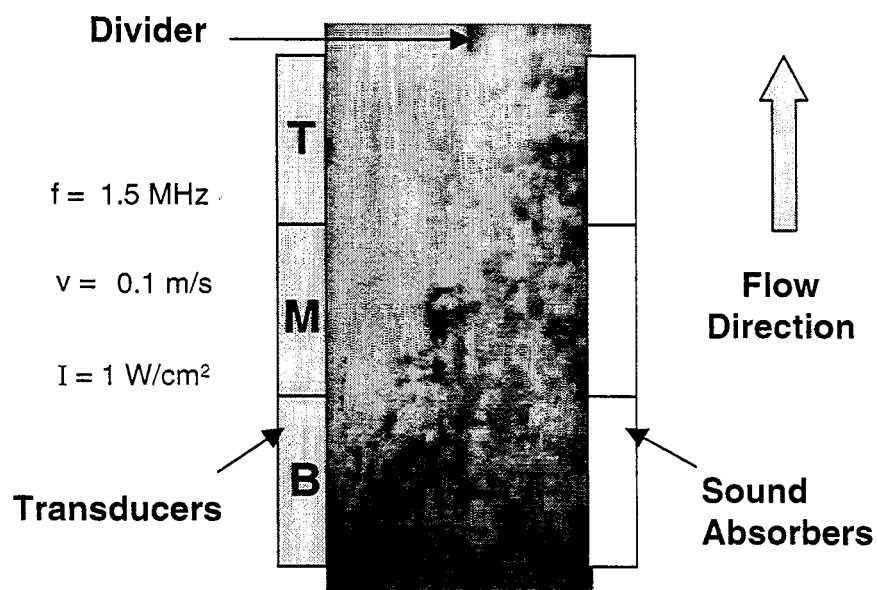


Fig. 9. Whitewater clarification using three 1.5 MHz transducers. The PEO/PFR level is 5 mg/L:10 mg/L.

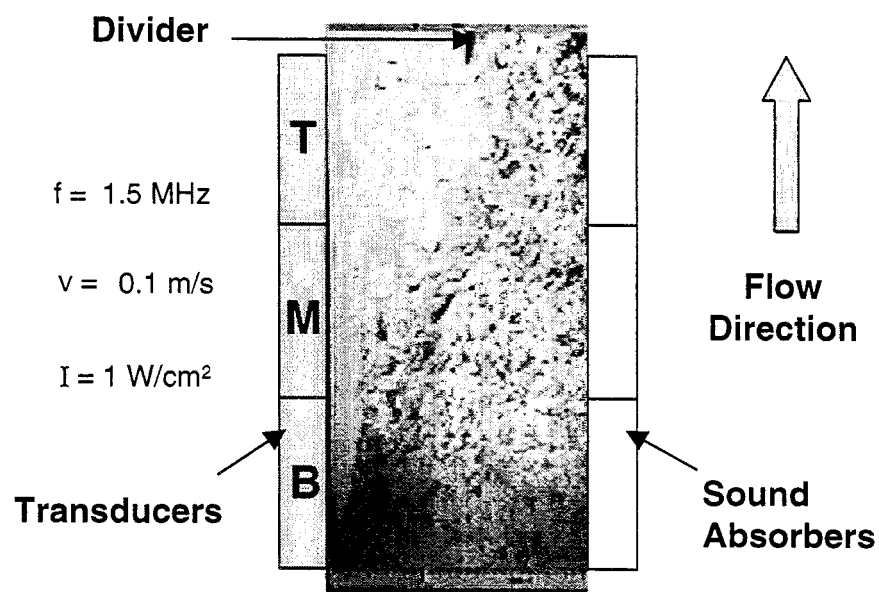


Fig. 10. Clarification recording using three transducers operating at 1.5 MHz. The PEO/PFR level is 2 mg/L:4 mg/L.

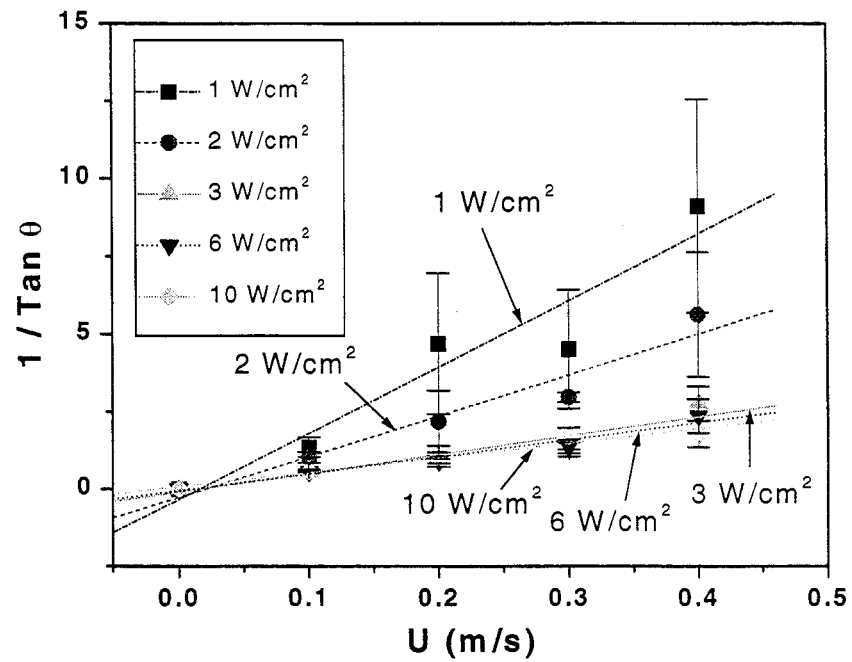


Fig. 11. Plot of $1/\tan \theta$ vs. U for different acoustic intensity levels at 150 kHz. Linear curve fitting from 0 to 0.4 m/s was used to determine the floc migration velocity v per acoustic intensity level. Results are presented in Fig. 13.

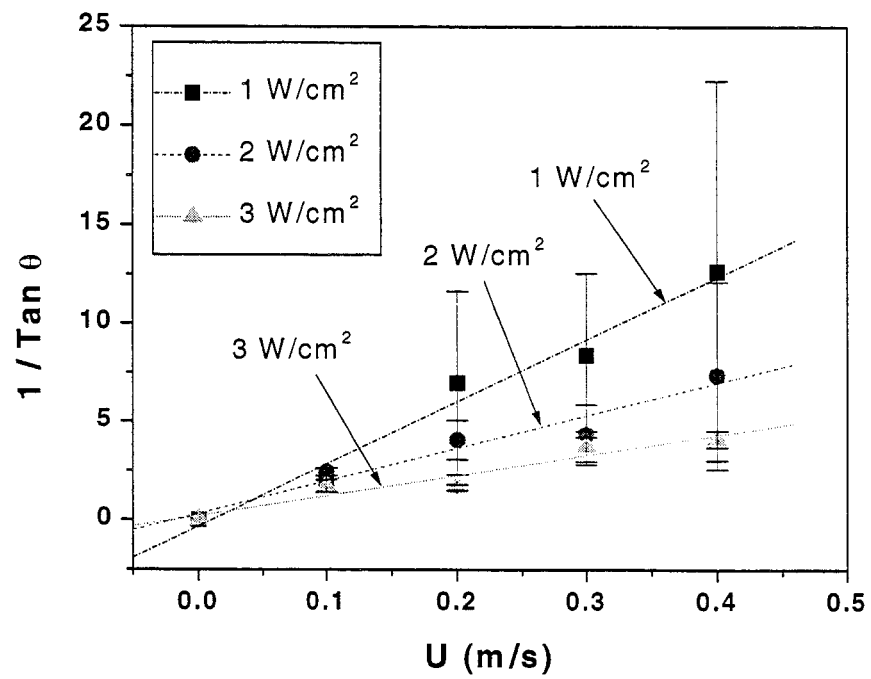


Fig. 12. Plot of $1/\tan \theta$ vs. U for different acoustic intensity levels at 1.5 MHz. Linear curve fitting from 0 to 0.4 m/s was used to determine the floc migration velocity v per acoustic intensity level. Results are presented in Fig. 13.

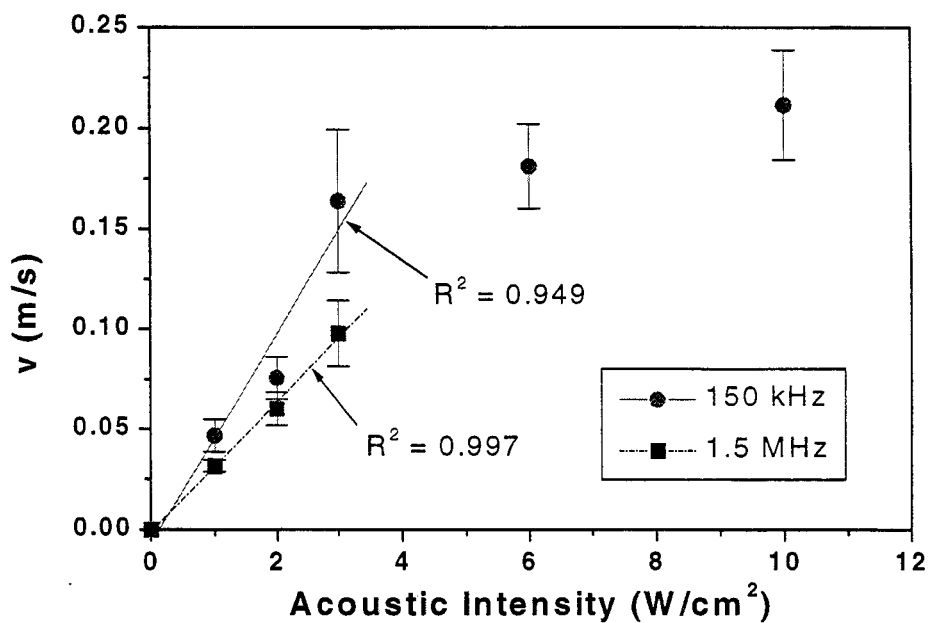


Fig. 13. Graph of the floc migration velocity versus acoustic intensity for measurements obtained at 150 kHz and 1.5 MHz. Linear curve fitting between 0 and 3 W/cm² was used to relate v and I : slope at 150 kHz: $0.052 \pm 0.008 \left(\frac{\text{m cm}^2}{\text{s W}} \right)$; slope at 1.5 MHz: $0.032 \pm 0.001 \left(\frac{\text{m cm}^2}{\text{s W}} \right)$.

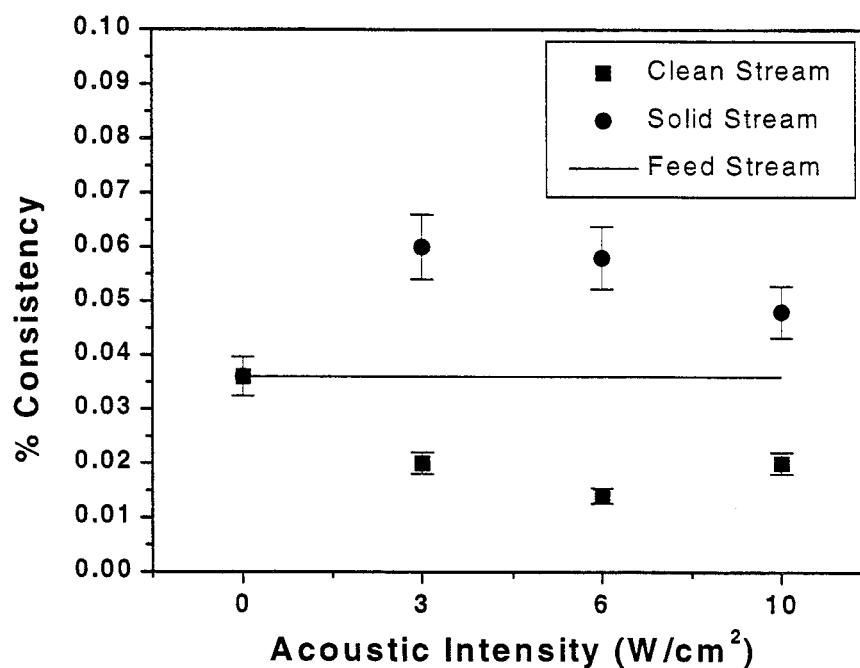


Fig. 14. Clean and concentrated streams consistency measurements vs. acoustic intensity for experiments performed at 150 kHz using the top transducer only. The flow velocity and flocculant dosage are set to 0.1 m/s and 5 mg/L:10 mg/L, respectively. The feed stream consistency is provided as a reference point for comparison.

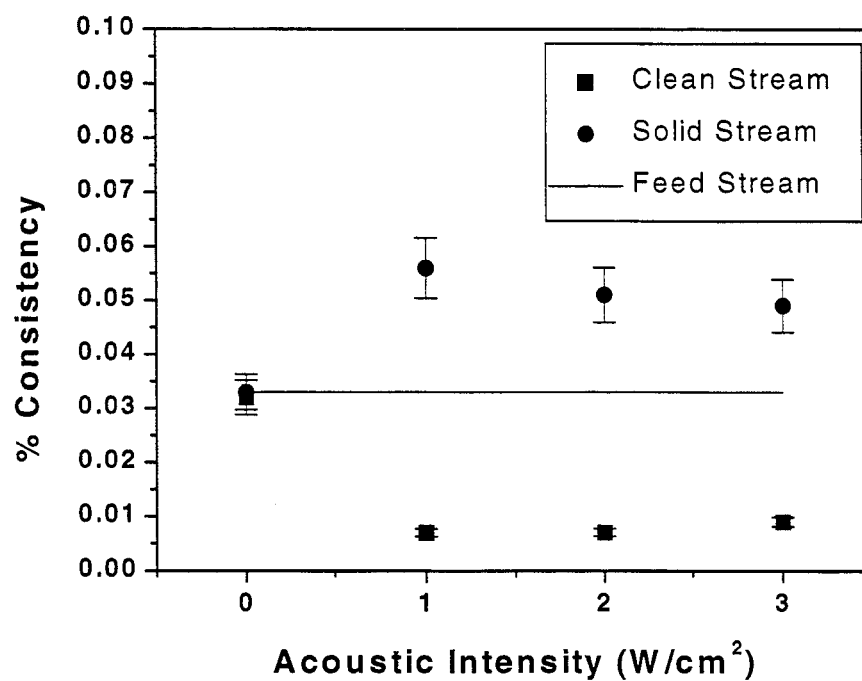


Fig. 15. Clean and concentrated streams consistency measurements vs. acoustic intensity for experiments performed at 1.5 MHz using three transducers. Flow velocity and flocculant dosage are set to 0.1 m/s and 5 mg/L:10 mg/L, respectively. The feed stream consistency is provided as a reference point for comparison.

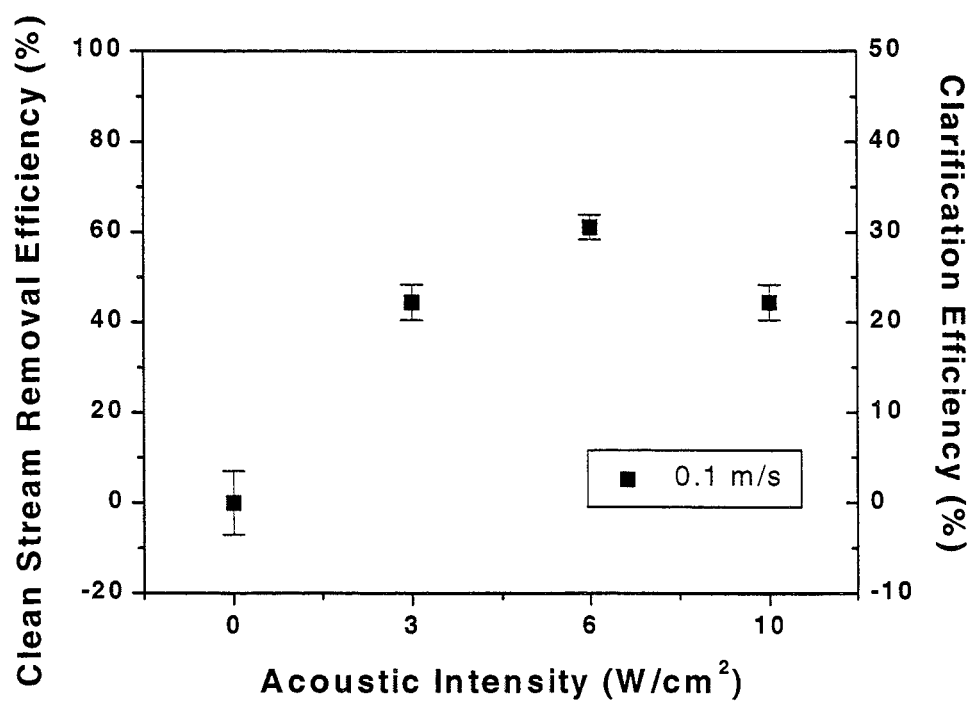


Fig. 16. Clean stream solids removal efficiency and clarification efficiency for the 150 kHz results shown in Fig. 14. Since the divider blade position is at the 50:50 position, the clarification efficiency cannot exceed 50%.

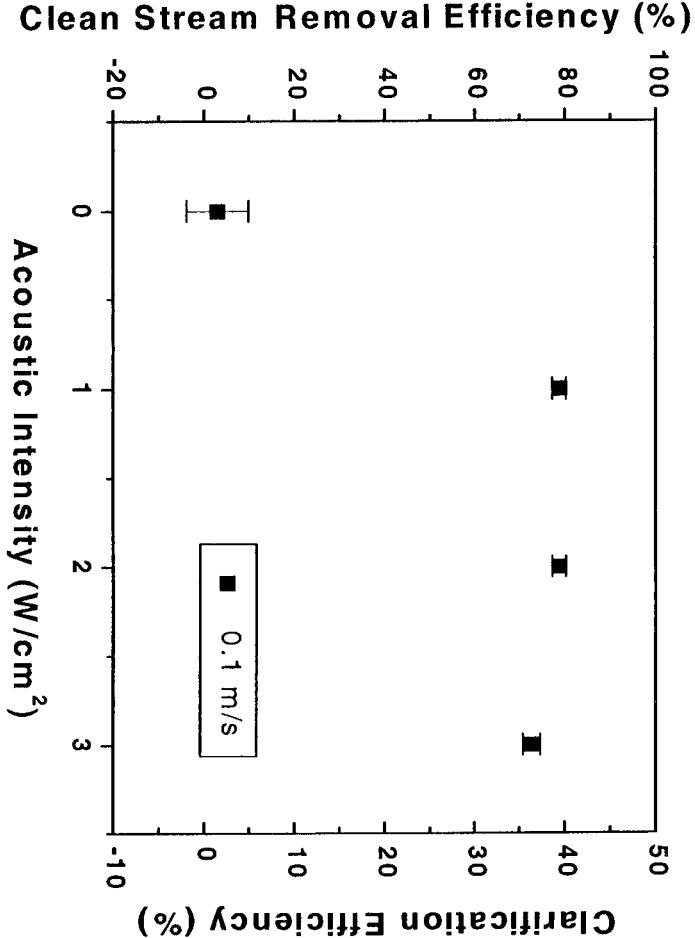


Fig. 17. Clean stream solids removal efficiency and clarification efficiency for the 1.5 MHz results displayed in Fig. 15.